Predation on Planted and Wild Bay Scallops (*Argopecten irradians irradians*) by Busyconine Whelks: Studies of Behavior Incorporating Acoustic Telemetry

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Supplemental Materials

VPS array setup

The 20 m x 20 m experimental grid was set up by divers and marked with cinder blocks to which surface floats were attached on 16 September 2013. Acoustic receivers were deployed on 26 September 2013, ~20 m outside of the experimental plot - with an inter-receiver distance of 30 m. A pentagonal shape was determined by InnovaSea (Dana Allen, pers. comm.) to be the most suitable configuration for optimizing estimates of spatial position in the experimental grid. Receivers were attached with cable ties to rebar stakes set in cement within 5-gal buckets and synchronization tags were attached to the tops of rebar stakes. Three additional fixed reference tags were deployed (center of the array, southwest and northwest corners of the grid) to improve positioning accuracy. Spatial acoustic coverage was calibrated on 30 September 2013, prior to field experiments, by having divers swim through the array with an acoustic tag. Finally, cement blocks tied to lines with surface buoys were placed ~ 2-3 m beyond the acoustic receivers to mark and protect the area from boat disturbance. A Trimble® GPS receiver with sub-meter resolution was used to record positions of the experimental grid corners and receivers; coordinates at the center of the grid were 41.03722936º N, 72.38780288º W.

Environmental parameters and measurements

Water temperature during each field experiment was recorded every 30 min with a submersible Tidbit® automatic temperature recorder. Salinity was measured with a YSI Pro 2030 multi-probe meter at the start and end of each experimental trial. Ranges of surface water temperature and salinity through all of the field experiments were 12.7 - 30.6 ºC and 29.0 - 29.6, respectively. Three replicate surficial sediment samples (to a depth of 5 cm) were taken at each of three locations within the 20 x 20 m grid; grain size fractions were later characterized according to Folk & Ward (1957). Sediment grain size analyses were conducted on samples taken at the start of field experiments. Of nine samples taken in three different grid sectors, sand comprised 85 – 96% of the grain size fractions. Mean and standard errors (SE) proportions for gravel, sand, and silt + clay fractions, respectively, were 0.060 (0.009); 0.926 (0.014) and 0.014 (0.008).

Hyperbolic positioning error (HPE) filter acoustic telemetry data

For acoustic telemetry data, a Hyperbolic Position Error (HPE) was estimated to provide a relative measure of the accuracy of each detection within the acoustic receiver array (Meckley et al. 2014). HPE filtering was based on criteria from Scheel and Bisson (2012). In general, the lower the HPE score, the more accurate the position estimate. In this study, the telemetry positioning array yielded over 32,424 detections across all 48 hr trials and, overall, HPEs were very low: 90% of the HPE's were < 1; mean = 1.5, median = 0.7 ± 0.1. The average HPE for fixed reference transmitters within the array (n=3) was 0.64 ± 0.08 SD throughout all trials. Average HPEm (Hyperbolic Position Error in meters) was 0.15m (95% CI: 0.0m-0.40m) for the fixed reference tags. Higher HPE values only occurred when whelks moved far outside the pentagonal acoustic array. Scheel and Bisson (2012) estimated that HPE scores < 20 are of sufficient accuracy for tracking fine-scale movements of octopus on the order of meters; therefore, we elected to filter our data to eliminate position estimates that were greater than 20. Using this approach, less than 0.004% of all the detections were removed.

Hidden Markov model (HMM) setup and fitting procedures

HMMs can identify several animal behavioral states, but users need to use realistic biological inference when constructing HMMs. Given the expected movement behavior of whelk is limited relative to other marine species, we employed two-state HMMs (encamped and exploratory) - which is the most common in the movement ecology literature (Bacheler et al. 2019). Encamped behaviors consisted of small step lengths and reduced angle direction variability; whereas, exploratory behavior is comprised of longer step lengths and wide variability of movement directionality. All models had gamma and von Mises family error distributions, for step length and angle, respectively (Bacheler et al. 2019).

Prior to fitting HMMs for each trial, we accounted for temporal irregularity and location measurement error by fitting our data to continuous-time correlated random walk models to each individual whelk track and specified the model to predict locations from observed data every four minutes (Johnson et al. 2008). Numerical maximum likelihood approaches were used to fit HMM models. Given that the maximum likelihood estimator could find a local maximum compared to the global maximum, initial values of step length and angle were selected randomly across a range of values and selected the model with the highest likelihood (Adam et al. 2019). To minimize the risk of parameter inestimability, each model was fitted 12 times across the random selection of parameters within the range of observed values. Parameter outputs from the base model with the global likelihood with no covariates were used as starting values in the HMMs with covariates to optimize model convergence (Michelot et al. 2016). Models with Akaike weights > .10 and delta AIC values < 7 were considered to have moderate support (Burnam and Anderson 2002).

References

Adam, T., Griffiths, C.A., Leos-Barajas, V., Meese, E.N., Lowe, C.G., Blackwell, P.G., Righton, D. and Langrock, R., 2019. Joint modelling of multi-scale animal movement data using hierarchical hidden Markov models. *Methods in Ecology and Evolution*, *10*(9), pp.1536-1550.

Bacheler NM, Michelot T, Cheshire RT, Shertzer KW (2019) Fine-scale movement patterns and behavioral states of gray triggerfish *Balistes capriscus* determined from acoustic telemetry and hidden Markov models. Fish Res 215:76–89. doi: 10.1016/j.fishres.2019.02.014

Burnham KP, Anderson DR (2002) A practical information-theoretic approach. Model selection and multimodel inference, 2nd ed. Springer, New York.

Folk RL, Ward WC (1957) Brazos River bar [Texas]; a study in the significance of grain size parameters. J Sed Res 27:3–26. doi: 10.1306/74d70646-2b21-11d7-8648000102c1865d.

Johnson DS, London JM, Lea M-A, Durban JW (2008) Continuous-time correlated random walk model for animal telemetry data. Ecology 89:1208–1215. doi: 10.1890/07-1032.1.

Meckley TD, Holbrook CM, Wagner C, Binder TR (2014) An approach for filtering hyperbolically positioned underwater acoustic telemetry data with position precision estimates. An Biot 2:7. doi: 10.1186/2050-3385-2-7.

Michelot T, Langrock R, Patterson TA (2016) moveHMM: an R package for the statistical modelling of animal movement data using hidden Markov models. Meth Ecol Evo 7:1308–1315. doi: 10.1111/2041-210x.12578.

Scheel D, Bisson L (2012) Movement patterns of giant Pacific octopuses, *Enteroctopus dofleini*. J Exp Mar Biol and Ecol 416:21-31. doi.org/10.1016/j.jembe.2012.02.004

Table S1. Summary of 2012-2014 laboratory experiments examining predation on bay scallops (*Argopecten irradians irradians*) by channeled (*Busycotypus canaliculatus*) and knobbed whelks (*Busycon carica*). Two size classes of channeled whelks (small = 113 - 139 mm shell length (SL); jumbo = 188 – 218 mm SL) were presented with two size classes of scallops (small = 21 – 30 mm shell height (SH) ; large = 49 – 62 mm SH) that were stocked at two densities (low = 10/m^2; high = 75/m^2). One size class of knobbed whelks (106 – 145 mm SL) was presented with the same sizes and densities of bay scallops. Damage to shells of predated scallops: No = no visible damage; Cr = cracked; Nch = notch: thin (<2 mm) chip at ventral margin, parallel to hinge; ND = not determined.

Dates	Water Temp. (C)	Whelk Species	Whelk Size	Scallop Size	Scallop Density	# of Replicates	Total # of Scallops Eaten	# Scallops Eaten per Whelk Per Day	Shell Damage
7/26-8/2/12	24.2-27.3	chan	small	large	low	5	0	0	
					high	5	7	0.200	7 No
							overall:	0.100	
8/16-22/12	~26.8	chan	small	small	low	5	0	0	
					high	5	0	0	
							overall:	0	
8/27-9/3/13	24.0-25.6	chan	jumbo	large	low	3	2	0.095	2 No
					high	3	3	0.143	2 No, 1 Cr
							overall:	0.119	
8/27-9/3/13	24.0-25.6	chan	small	large	low	2	2	0.143	1 No, 1 Cr
					high	2	0	0	
							overall:	0.071	
9/24-30/13	17.6-18.9	chan	small	small	low	4	0	0	
					high	5	1	0.033	1 ND
							overall:	0.019	
10/23-30/13	11.4-11.5	chan	small	small	low	5	0	0	
					high	5	0	0	
							overall:	0	

Dates	Water Temp. (C)	Whelk Species	Whelk Size	Scallop Size	Scallop Density	# of Replicates	Total # of Scallops Eaten	# Scallops Eaten per Whelk Per Day	Shell Damage
11/6-12/13	10.1-13.1	chan	small	large	low	5	0	0	
					high	5	0	0	
							overall:	0	
10/18-24/14	14.2-16.3	knob	small	small	low	4	2	0.083	1 Ch, 1 Nch
					high	4	8	0.333	6 Nch, 1 No, 1 Cr
							overall:	0.208	
10/31-11/6/14	8.3-14.3	knob	small	small	low	4	1	0.042	
					high	4	1	0.042	1 Nch, 1 ND
							overall:	0.042	

Table S2. Numbers/sizes of live wild scallops (0+ yr = juvenile, 1+ yr = adult) and resident whelks (channeled and knobbed) which were removed from the four 10 m x 10 m sectors of the experimental grid off Cedar Beach, Southold immediately prior to the start of field predation trials conducted in 2013. Whelks were removed out to ~3 m beyond the perimeter of the four sectors. Scallop shell height (SH) and whelk shell length (SL) were measured to the nearest mm. NM = not measured.

Start Date	#	Wild Scallops (0+ yr) Mean (SE) SH	#	Wild Scallops (1+ yr) Mean (SE) SH	#	Resident Channeled Whelk Mean (SE) SH	#	Resident Knobbed Whelk Mean (SE) SH
7 Oct	704	NM	68	NM	0		6	NM
16 Oct	173	42.0 (0.3)	23	67.6 (0.7)	3	156.0 (15.0)	32	155.8 (3.3)
21 Oct	16	44.1 (1.0)	7	69.5 (2.7)	0		39	161.2 (3.8)
28 Oct	16	NM	3	NM	4	142.5 (4.5)	36	152.5 (3.3)
30 Oct	82	NM	4	NM	3	139.3 (6.1)	4	142.2 (4.5)

Table S3. Size and sex of tagged channeled whelks released in field telemetry experiments off Cedar Beach, Southold, NY, October – November 2013. Individuals with blank sex information did not have sex recorded.

Start Date	Burial Tag #	Acoustic Tag ID #	Shell Height (mm)	Shell Width (mm)	Total Wet Wt (g)	Sex
7 Oct	1	12715	131	68.5	126.8	
	2	12716	130	69	116.2	
	3	12717	131	77.5	123.5	
	4	12718	132	32?	122.6	
	5	12719	135.5	78.5	171.1	
	6	12720	134	74	141.9	
	7	12721	134	74	140.3	F
	8	12722	135.5	73.5	148.0	
	9	12723	127	71	155.2	M
	10	12724	134.5	68	139.8	
16 Oct	11	12715	125	72	137.3	F
	13	12716	135	69	132.2	M
	14	12717	132	69	145.5	F
	16	12718	137	70	142.1	F
	17	12719	137	71	146.0	M
	19	12720	134	69	145.4	M
	28	12721	125	67	110.4	F
	33	12722	134	72	158.8	F
	45	12723	132	70	141.4	F
	56	12724	132	68	144.1	F
21 Oct	12	12715	134	70	174.2	M
	15	12716	135	71	148.3	M
	18	12717	128	72	169.9	M
	21	12718	134	69	129.5	M
	22	12719	137	73	166.7	
	23	12720	134	73	159.4	M
	24	12721	134	77	183.7	M
	26	12722	136	72	143.3	
	30	12723	131	70	138.2	
	31	12724	130	71	165.6	

Start Date	Burial Tag #	Acoustic Tag ID #	Shell Height (mm)	Shell Width (mm)	Total Wet Wt (g)	Gender
28 Oct	59	12715	123	67	102.2	M
	34	12716	131	72	109.1	F
	49	12717	135	69	130.8	F
	38	12718	104	50	68.1	M
	25	12719	134	70	119.6	M
	27	12720	135	68	120.6	
	40	12721	131	67	114.0	M
	54	12722	116	61	83.2	F
	51	12723	134	71	133.8	
	36	12724	132	68	128.9	M
30 Oct	55	12715	125	71	137.4	M
	47	12716	131	69	143.4	M
	43	12717	135	69	189.8	M
	37	12718	140	76	181.5	M
	46	12719	134	73	185.7	M
	35	12720	133	71	132.8	F
	42	12721	135	73	154.4	M
	50	12722	137	77	179.2	M
	53	12723	134	74	137.2	M
	48	12724	134	72	153.1	M

Table S4. Numbers of cluckers recovered before (pre) and at the end of (post) field predation experiments conducted off Cedar Beach, Southold in 2013. Grid cell # 1, 2, 3 4 represent the NE, NW, SW and SE quadrants, respectively, of the 10 m x 10 m experimental grid. Numbers of cluckers (post) were those which had accumulated after removal of all cluckers at the end of the prior experiment - except on 30 October, when this experiment was run immediately after the prior one. Total clucker numbers for a given grid cell represent those found inside that cell plus cluckers that were collected beyond the perimeter of adjacent grid (out to ~3 m to the W, E and ~5 m to the N, S); numbers in parentheses = # of natural scallop cluckers; ND = not determined. Shading indicates that grid cell was planted at the high scallop density (target = 75/m^2). ɔ = wild cluckers; * = includes 8 cluckers that were directly observed to have been eaten by knobbed whelks on 16 October 2013 in unspecified grid cells.

Expt	**Cell 1**			**Cell 2**			**Cell 3**			Cell **4**			
Dates	Inside	Outside	Total	Inside	Outside	Total	Inside	Outside	Total	Inside	Outside	Total	**Total**
16 Oct (pre)	1	ND	1	ND	ND	ND	1	ND	1	ND	ND	ND	2ɔ
18 Oct (post)	48	ND	48	1	ND	1	15	ND	15	15	ND	15	87*
21 Oct (pre)	147	12	159	0	0	0	78	ND	78	36(1)	6	42	279
24 Oct (post)	22	ND	22	16	ND	16	71	ND	71	87	ND	87	196
28 Oct (pre)	25	15	40	10	3	13	50	17	67	61	67	128	248
30 Oct (post)	41	5	46	41	6	47	29	22	51	78	35	113	257

Grand Total = 1069

Table S5. Cumulative numbers of live planted scallops recovered from the experimental area off Cedar Beach, Southold at the end of the last predation experiment on 30 October 2013. Totals include scallops recovered from inside the four 10 m x 10 m grid cells and beyond the perimeter of respective cells (out to ~3 m to the W, E and ~5 m to the N, S). Low, high = low and high planting densities: target = 10 and 75/m^2, respectively.

	Live		
	Inside	Outside	Total
Cell 1 (Low)	1900	91	1991
Cell 2 (High)	1900	184	2084
Cell 3 (Low)	1300	270	1570
Cell 4 (High)	4400	359	4759
	9500	**904**	**10404**

Table S6. Opportunistic observations of (A) channeled and (B) knobbed whelk predation on bay scallops made while diving in the Peconic Bays, 2011-2015. Off CB = in and near experimental grid off Cedar Beach; Sh= shell; SL= whelk shell length; SH= scallop shell height.

(A) **Channeled Whelks**

Date	Location	Sediment Type	Depth (m)	Water Temp (ºC)	Whelk SL (mm)	Scallop SH (mm)	Notes
11 Oct 2011	Great Peconic Bay	Sand	4.3	18.6	174	48	mostly buried; scallop entirely engulfed
16 Oct 2013	Southold (off CB)	Sand	3	17.7	135	75	
28 Oct 2014	Southold (off CB)	Sand	3	15.6	160	65	outer lip of whelk was inserted between scallop valves at ventral margin, with hinge held firmly in place by foot and perhaps operculum which was immediately distal
22 Oct 2015	Flanders Bay	Sand	3.1	15.0	171	60	scallop entirely engulfed by whelk foot

(B) **Knobbed Whelks**

Date	Location	Sediment Type	Depth (m)	Water Temp (ºC)	Whelk SL (mm)	Scallop SH (mm)	Notes
27 Sep 2012	Northwest Harbor	Sand	1-2	21.7	238	81	
27 Sep 2012	Northwest Harbor	Sand	1-2	21.7	213	76	
27 Sep 2012	Northwest Harbor	Sand	1-2	21.7	216	78	
25 Oct 2012	Southold Bay	Sand	2.8	16.7	161	57	scallop entirely engulfed by whelk foot
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	133	27	
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	132	22	
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	190	29	scallop completely inside whelk shell aperture
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	143	31	scallop completely inside whelk shell aperture
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	156	26	scallop already consumed
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	195	29	scallop still alive
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	163	27	
16 Oct 2013	Southold (off CB)	Sand	2-3	17.4-17.6	155	29	
2 Nov 2013	Southold (off CB)	Sand	4	13.9	146	61	
4 Nov 2013	Sag Harbor	Mud	3-5	12.8	173	69	
14 Jul 2014	Orient Harbor	Mud	5-6	23.9	147	56	
28 Oct 2014	Southold (off CB)	Sand	3	15.6	215	67	
29 Jun 2015	Hog Neck Bay	Sand/Sh	3.7	22.8	164	31	notch evident at ventral margin of scallop shell

Figure S1. Notching of the ventral margins of bay scallop shell valves, a characteristic type of damage inflicted by knobbed whelks, *Busycon carica*, during predatory attacks – as seen in laboratory experiments and field observations.

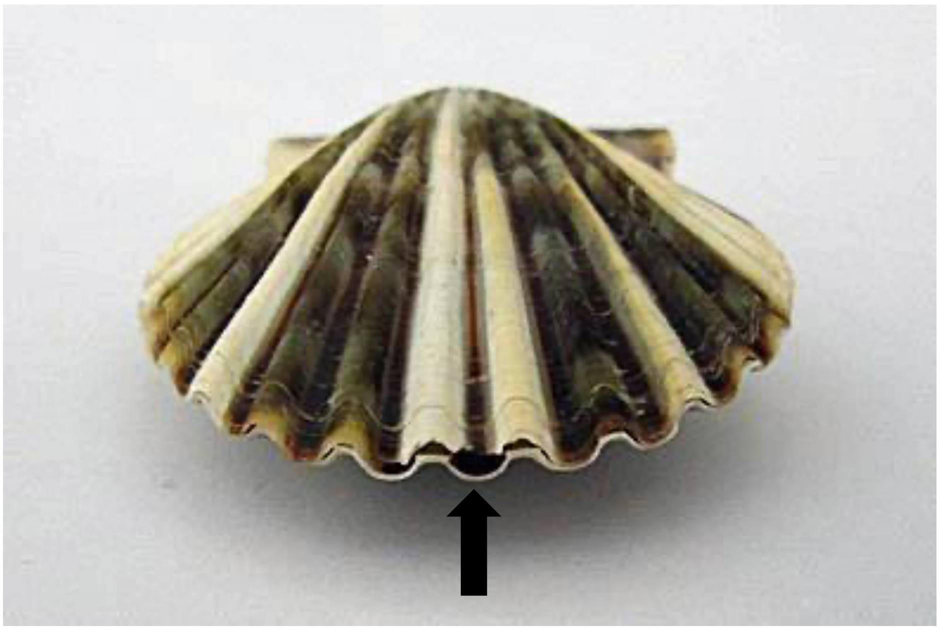

Figure S2: Amount of time each individual tagged whelk spent in each of the two states, encamped (pink) and exploratory (blue), in the best fit 2-state hidden Markov models for each respective trials. Trials 1, 2, 3, 4, 5 are denoted by figures A, B, C, D, and E, respectively.

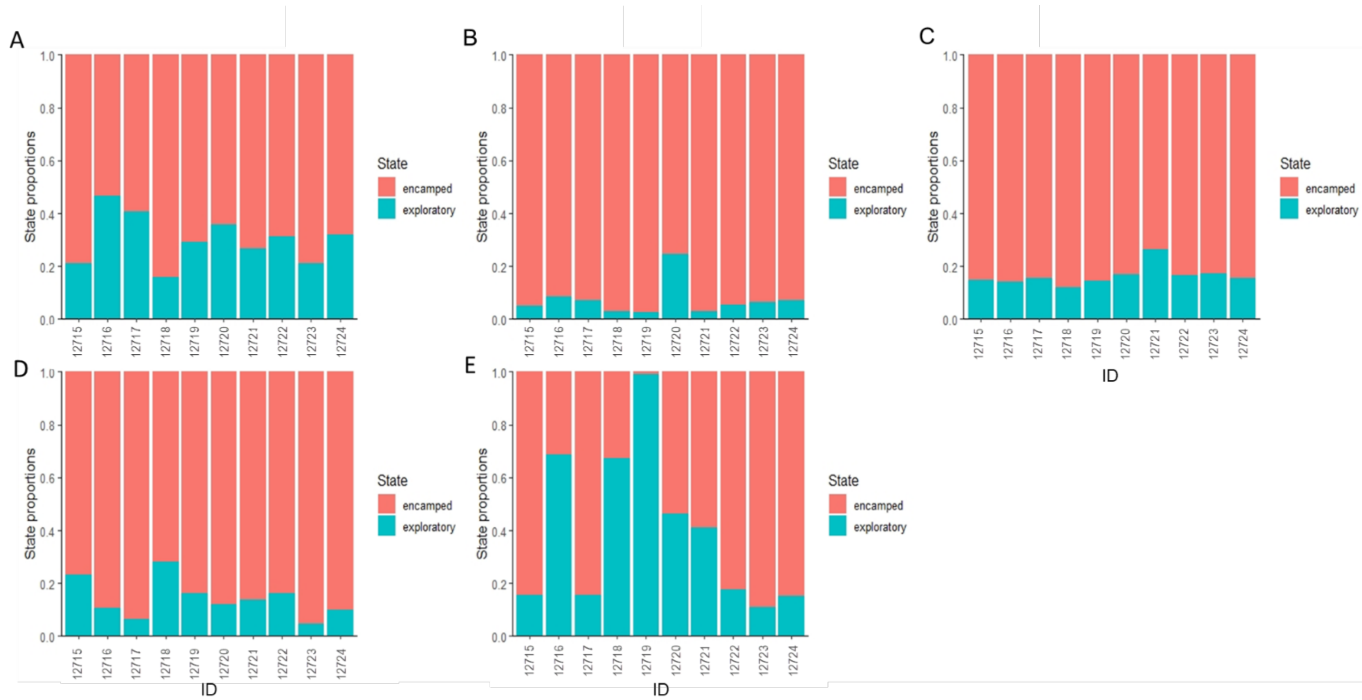

Figure S3. Each plot represents a unique individual whelk's position in UTM coordinates (meters) and movement tracks across from each field trial with acoustic telemetry. Trial numbers are denoted in the upper right corner of each plot. Transparent grey circles denote the center of the experimental grid where whelks were initially released.

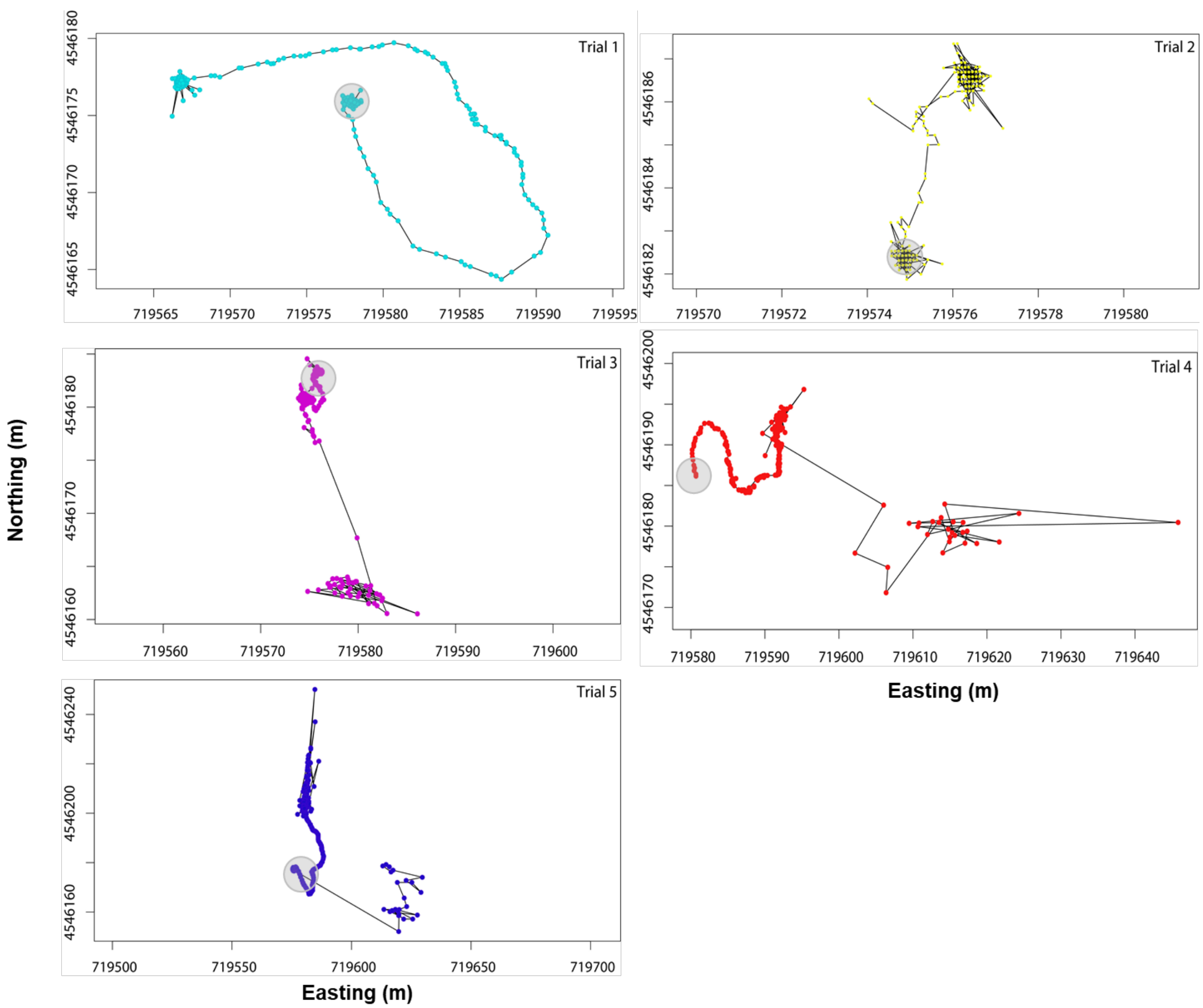

Figure S4. Mean stationary state distributions between predominant tide cycles (flood or ebb) of whelk behavioral states from trials 3 (A) and 4 (B). Error bars indicated 95% confidence intervals.